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Performance Characteristics of Waste Glass Powder Substituting Portland Cement in Mortar Mixtures

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Abstract. In the present work, soda-lime glass cullet (flint, amber, green) and special glass cullet (soda-alkaline earth-silicate glass coming from low pressure mercury-discharge lamp cullet and incandescent light bulb borosilicate glass waste cullet) were ground into fine powders in a laboratory planetary ball mill for 30 minutes. CEM I 42.5N Portland cement was applied in mortar mixtures, substituted with waste glass powder at levels of 20% and 30%. Characterisation and testing of waste glass powders included fineness by laser diffraction particle size analysis, specific surface area by nitrogen adsorption technique, particle density by pycnometry and chemical analysis by X-ray fluorescence spectrophotometry. Compressive strength, early age shrinkage cracking and drying shrinkage tests, heat of hydration of mortars, temperature of hydration, X-ray diffraction analysis and volume stability tests were performed to observe the influence of waste glass powder substitution for Portland cement on physical and engineering properties of mortar mixtures.

1. Introduction

The concrete industry is improving its sustainability performance and as well as meeting this through cement technology is increasingly moving towards the use of recycled aggregates [1]. Waste glass is one of the least recycled materials in the majority of countries as it requires relatively large amounts of energy to be consumed to melt the cullet [2]. The quantity of treated waste glass has risen by about 25% within the last 10 years due to an improved waste glass collecting system in Latvia, notwithstanding the glass waste recycling infrastructure still suffers from the lack of an adequate network of local recycling companies [3] and alternative solutions are required to solve the problem of the stockpiled waste glass. Being amorphous and having relatively high silicon and calcium contents, glass is pozzolanic or even cementitious especially when the fineness of glass powder is much greater than that of Portland cement. Caijun Shi has stated in [4] that ground glass possesses pozzolanic reactivity, but cannot be used as a cement substitution in conventional concrete because of potential alkali-aggregate reaction. But when the particle size of glass powder is less than 75 μm , silica may dissolve relatively quickly, reacting with free portlandite ($\text{Ca}(\text{OH})_2$) and acting as a pozzolanic material [5], giving possible control over the alkali-silica reaction in concrete, therefore making this material a possible substitute for Portland cement [6].



2. Materials and Methods

2.1. Materials

The constituent materials used in the laboratory to produce mortar mixtures comprised:

- (i) *Portland cement (PC)*: CEM I 42.5N with specific surface area of 388 m²/kg (Blaine); soundness of 1.0 mm (Le Chatelier); setting time of 122/220 min (initial/final); compressive strength at 28 days of 55 MPa; mineral composition (mass - %) C₃S 51.7%, C₂S 19.3%, C₃A 5.4%, C₄AF 15.90%; density of 3150 kg/m³; particle size distribution is shown in figure 1.
- (ii) *Waste glass powders*: soda-lime glass cullet (flint (F), amber (A), green (G)) and special glass cullet (soda-alkaline earth-silicate glass coming from low pressure mercury-discharge lamp cullet (L) and incandescent light bulb borosilicate glass waste cullet (D)) were subjected to grinding using a planetary ball mill (Retsch PM 400, equipped with 4 steel jars of 500 ml capacity each), operating at 300 rev · min⁻¹ for 30 minutes. Hardened steel spheres with 17 mm diameter and 430g mass per steel jar were used as grinding media. Characterisation included fineness by laser diffraction particle size analysis (see figure 1), specific surface area by nitrogen adsorption technique, density by specific gravity bottle/pycnometer and chemical composition by X-ray fluorescence spectrophotometric analysis (shown in the table 1).
- (iii) *Water* used within the mixtures was simple tap water, clean and free from impurities with conductivity ranging between 80 and 85 µS/cm and pH being 7.5 ± 1.

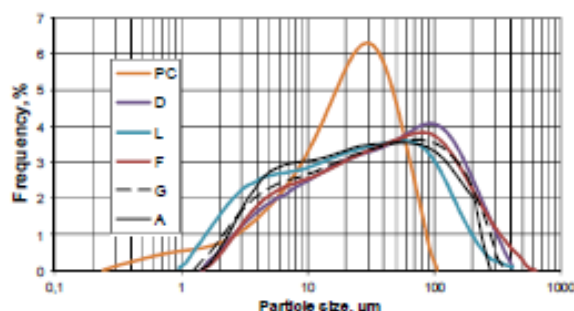


Figure 1. Particle size distribution of Portland cement and waste glass powders

Table 1. Chemical composition, fineness and density of Portland cement and waste glass powders

	Bulk oxide, w/w %											Fineness	Density,
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O	K ₂ O	MnO	MgO	TiO ₂	SO ₃	P ₂ O ₅	m ² /kg	kg/m ³
PC	17.93	5.22	2.97	62.03	0.20	1.76	0.140	4.06	0.360	3.76	0.440	388	3150
D	71.14	2.60	0.17	1.32	3.30	1.70	0.006	0.62	0.006	0.00	0.023	608	3688
L	65.52	1.22	0.11	5.11	12.35	1.88	0.010	2.95	0.027	0.14	0.038	542	2767
F	69.61	1.34	0.08	11.30	11.21	0.56	0.008	0.46	0.028	0.13	0.021	502	2741
G	67.80	1.53	0.36	10.93	11.09	0.55	0.018	1.58	0.062	0.03	0.023	463	2723
A	69.26	1.42	0.43	8.89	11.43	0.51	0.018	3.08	0.052	0.01	0.026	542	2843

2.2. Mixture proportions

The control mortar mixture and the various mortar mixtures with waste glass powders (WGP) as Portland cement substitute (at 20% and 30%) were mixed in a laboratory mortar mixer according to EN 196-1:2005. The water/cement ratio was selected to be w/c = 0.29. Where cement substitution by glass powder was applied, the water/binder ratio was changed to w/b = 0.34 (20% WGP) and w/b = 0.37 (30% WGP), however, the water/cement ratio was kept constant at w/c=0.29.

2.3. Mechanical and physical properties

Cubic (50 mm × 50 mm × 50 mm) specimens were prepared in order to determine compressive strength. Mortars were cast into the moulds; the exposed surface of the specimens was covered with

polyethylene film to prevent moisture evaporation. Demoulding was carried out 24 hours after production and the specimens were cured in water at a temperature of $+20\pm 2^\circ\text{C}$ for 28 days. Compressive strength tests were conducted on a Controls (model 50-C56G2) semi-automatic compression machine (3000 kN). The compressive strength of mortar specimens was determined at the ages of 7, 28, 84, 118, 270 and 660 days in accordance with LVS EN 12390-3:2009/AC:2011 and using triplicate specimens at each age. Physical properties of hardened mortar samples such as density (by the hydrostatic weighing method LVS EN 12390-7:2009) and water absorption were also included.

2.4. Early age shrinkage cracking and drying shrinkage [7]

The test method according to the Hungarian standard MSZ 523-5:1975 was used for the drying shrinkage tests. Three $40\text{ mm} \times 40\text{ mm} \times 160\text{ mm}$ prismatic specimens were prepared for each series to the drying shrinkage tests. The ring test method was performed for the early age shrinkage cracking. The substitution of 20% and 30% per mass of Portland cement seemed to be applicable in view of drying shrinkage with total deformation up to 2.5 % in the period of 592 days. However, the increase in waste glass powder addition led to an increase in drying shrinkage. The WGP addition contributed to a slowdown in the rate of hydration of the cement mortar, so the early age shrinkage cracking tendency became more prominent, which could be seen in the longer cracking time result during the ring tests. In the point of view of early age shrinkage cracking tendency, the soda-lime WGP needed from 40 to 47 hours for the appearance of the first early age crack, whereas the special WGPs required some longer time, from 44 to 53 hours, which in both cases was about 35% longer compared to the time for the reference Portland cement mortar.

2.5. Heat of hydration

Isothermal conduction calorimetric tests were carried out on mortar samples with cement and waste glass powder (as Portland cement substitute, at levels of 20% and 30%) using an I-Cal 4000 Isothermal Calorimeter in compliance with ASTM C1679, applying curing temperatures of less than 50°C and total test times of not less than 72 hours.

2.6. Temperature rise under semi-adiabatic conditions

The temperature rise under semi-adiabatic conditions inside the concrete mixtures was measured by an apparatus consisting of a plywood box with a 50 mm insulation layer of Finn foam FI – 300 (λ of 0.033 W/(mK)) and embedded four demountable $50\text{ mm} \times 50\text{ mm} \times 50\text{ mm}$ plywood moulds with thermocouples located in the center of one face of each mould and connected to a data transmitting device. Sample temperature was monitored until it reached its highest value and whilst maintaining an ambient air temperature of $20\pm 0.5^\circ\text{C}$ outside of the box [8].

2.7. X-ray diffraction (XRD) analysis

The hardened cement mortars were used for XRD analysis. The XRD measurements were performed with a Hilton-brooks HG62 diffractometer of using $\text{CuK}\alpha$ radiation ($k = 1.540562\text{ \AA}$). The angular range was from 3 to 60° 2-Theta with a step width of 0.1° and a measuring time of 3 s/step. For XRD quantitative phase analysis based on Rietveld refinement, the samples were mixed with 5 wt.% Al_2O_3 as internal standard (corundum, a standard material widely used in XRD analysis due to having only a few, but tall and narrow peaks). The Rietveld fitting procedure also permits the estimation of the amount of non-crystalline phases.

2.8. Volume stability

Mortar bar specimens were prepared following the procedure described in RILEM TC 106 AAR-2 “Detection of potential alkali-reactivity of aggregates – the ultra-accelerated mortar-bar test” [9]. There were 33 mortar bar specimens prepared for cement and five types of WGPs: 3 reference mortar bar specimens, 15 mortar bar specimens with cement substitution by WGPs at 20 wt. % and again 15

mortar bar specimens with cement substitution by WGP's at 30 wt. %. The mortar bar specimens were cured at $20 \pm 2^\circ\text{C}$ and 95% relative humidity in the moulds, demoulded after 24 ± 2 h when their initial length was measured. The specimens were then placed in water, transferred to an oven at temperature $80 \pm 2^\circ\text{C}$ for 24 h, removed from the water and the length measured immediately before the temperature could drop substantially. Thereafter the specimens were placed in 1 M NaOH solution preheated to a temperature of $80 \pm 2^\circ\text{C}$, the containers were sealed and placed in an oven at $80 \pm 2^\circ\text{C}$ (for 14 more days). Length measurements were taken only on the 7th and 14th days by means of a digital length comparator (± 0.001 mm accuracy).

3. Results and discussions

The development of the compressive strength is indicated in figures 2 to 4 for the five WGP's in comparison to that of neat cement mortar. A rapid development of the compressive strength is visible between the ages of 28 to 118 days, being faster than that of the hardened neat cement mortar that is attributed to a supposed very active hydration of the WGP's during that period of time. The application of special waste glass cullet at 20% substitution resulted in higher compressive strengths than the application of soda-lime cullet and also compared to cases with 30% substitution.

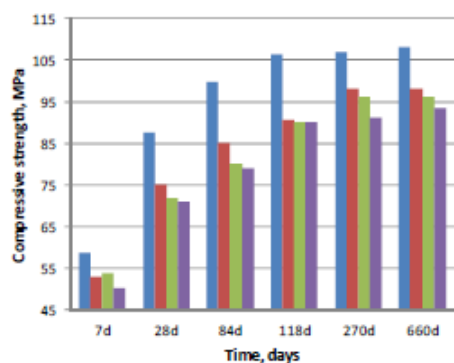


Figure 2. The evolution of compressive strength of mortar specimens, at 30% soda-lime WGP's substitution for PC

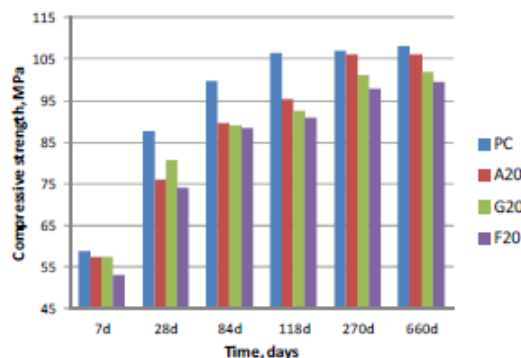


Figure 3. The evolution of compressive strength of mortar specimens, at 20% soda-lime WGP's substitution for PC

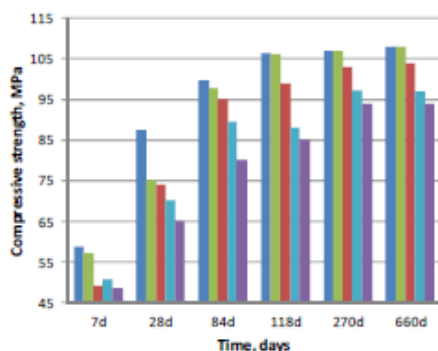


Figure 4. The evolution of compressive strength of mortar specimens, at 20% and 30% special WGP's substitution for PC

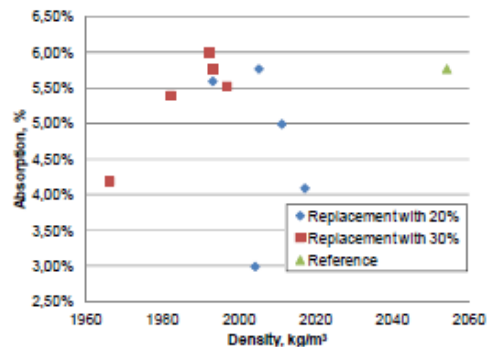


Figure 5. Absorption and density of mortar specimens, at 20% and 30% WGP's substitution for PC

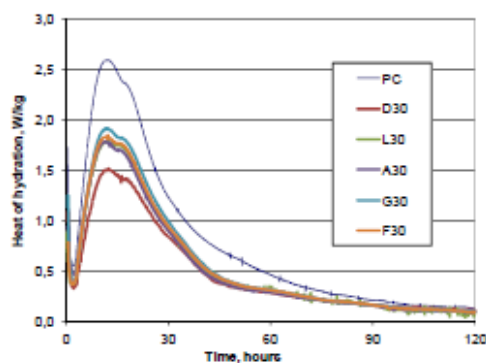


Figure 6. The evolution of the heat rate of a cement mortar (CEM I, w/b=0.29), at 30% WGP substitution for PC

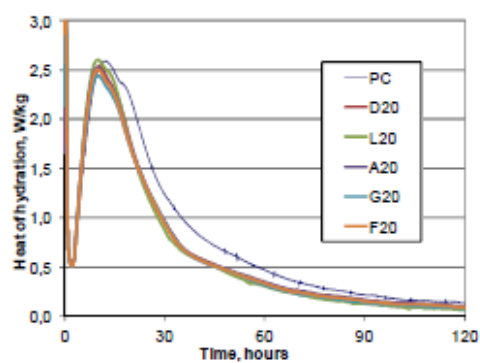


Figure 7. The evolution of the heat rate of a cement mortar (CEM I, w/b=0.29), at 20% WGP substitution for PC

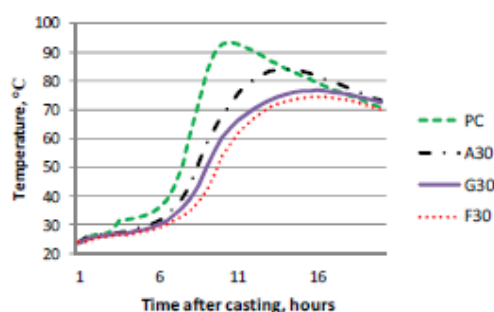


Figure 8. The temperature rise of a cement mortar (CEM I, w/b=0.29), at 30% soda-lime WGP substitution for PC

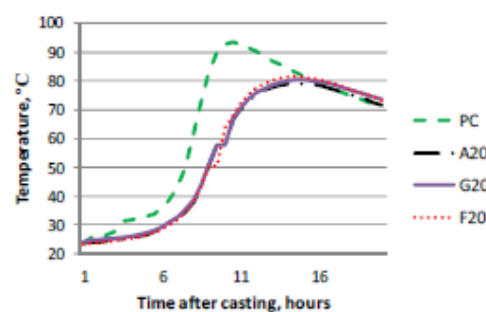


Figure 9. The temperature rise of a cement mortar (CEM I, w/b=0.29), at 20% soda-lime WGP substitution for PC

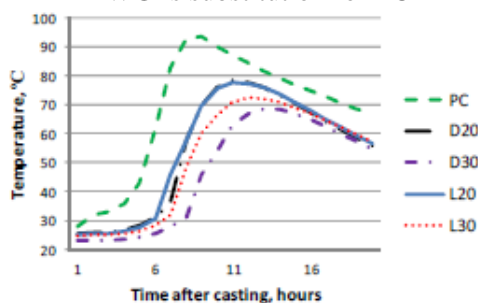


Figure 10. The temperature rise of a cement mortar (CEM I, w/b=0.29), at 20% and 30% special WGP substitution for PC

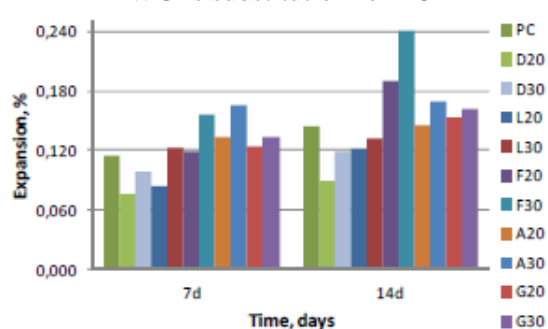


Figure 11. Volume stability of mortar specimens, at 20% and 30% WGP substitution for PC

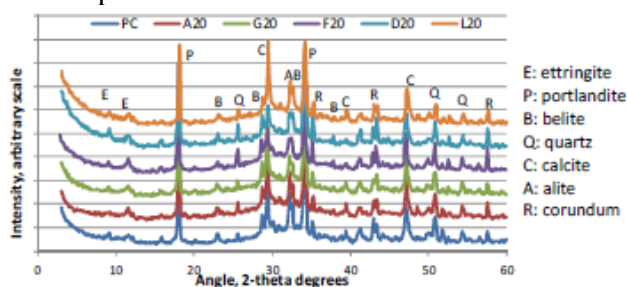


Figure 12. X-ray diffractograms of hydrated mortars, at 20% WGP substitution for PC

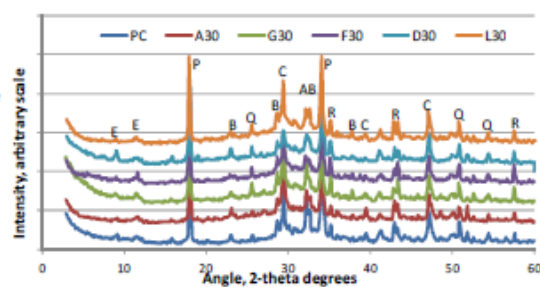


Figure 13. X-ray diffractograms of hydrated mortars, at 30% WGP substitution for PC

The significant effect on the compressive strength development is due to the fineness and chemical composition of WGP. The cement substitution with D20 WGP and A20 WGP gives equal compressive strength to Portland cement at the later age (see figures 3 and 4). The absorption and density of mortar specimens depending on the substitution level is shown in figure 5. It can be seen that a higher substitution level gives lower densities and increases the rate of absorption of the specimens; this may be attributed to the higher fineness of WGP in comparison to Portland Cement (see table 1). The heat rate evolution of cement mortars represented in the two diagrams in figures 6 and 7 confirms the effect of a decreased heat rate when substituting cement mortar with waste glass at higher substitution levels, especially when using D30 WGP (see figure 6). The temperature rise curves are shown in figures 8 to 10. The peak value of the temperature within the reference mortar specimen was clearly defined and took place approximately after 10 h (93°C). In contrast, for the specimens with WGP this was retarded up to 5 hours later with temperatures ranging from 68°C to 84°C. The ASR mortar expansion is demonstrated in figure 11. Experimental results have shown that both particle size and chemical composition influence expansion during the alkali-silica reaction; inasmuch as finer glass particles exhibit considerably lower expansion; whilst pozzolanic activity increases as fineness increases, also $\text{Na}_2\text{O}_{\text{eq}}$ of Portland cement has strong impact [6]. Fine particles of waste glass powder also tend to perform a relatively rapid pozzolanic reaction with Portland cement on the contrary to the much slower alkali-silica reaction. The mortar expansion rate decreases with the substitution of cement by finely ground waste glass powders, in particular for D20 WGP. The X-ray diffraction (XRD) analysis (see figures 12 and 13) indicates that inclusion of WGP does affect chemical reactions in the mixtures. Less unhydrated material (e.g. combined residual alite and belite contents) was detected in the samples made with WGP than the level of substitution for Portland cement may have caused. Rietveld curve fitting shows unhydrated material being 11.4% in the PC sample, whereas, with removal of the dilution effect of substitution, 11.2, 10.8, 10.7, 10.2 and 10.1% in A20, D20, F20, L20 and G20, as well as 9.6, 9.3, 8.9, 8.7 and 8.3% in A30, F30, L30, G30 and D30, respectively. However, these sequences may not directly reflect any order of reactivity, as there are other important factors, such as fineness and packing, to be considered when assessing the mechanical performance of the mixtures.

4. Conclusions

Considering the performance of different waste glass types as finely ground waste glass powders which can partially substitute Portland cement, it can be concluded that this by-product can be applied in concrete technology. The study has identified important effects on mechanical and durability properties when special glass cullet (low pressure mercury-discharge lamp cullet and incandescent light bulb borosilicate glass waste cullet) was used in comparison to soda-lime cullet, for example, increased compressive strength up to 10% at later ages due to the up to 30% higher obtained fineness by the grinding process; lower mortar expansion ($< 0.12\%$) during alkali-silica reaction; up to 20% lower heat rate and up to 10% lower peak hydration temperature and more favorable early age shrinkage cracking tendency, and indicated that finely ground waste glass powder is a valuable Portland cement substitute. The use of waste glass powder in concrete industry may moderate the problem of dumped waste glass and reduce CO_2 emissions into the atmosphere by decreasing the proportion of Portland cement in unit volume of concrete produced.

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